

Final Report for NAG5-11473; PI -- Linnea M. Avallone

This grant funded preparations for and participation in NASA's CRYSTAL-FACE mission, post-mission calibration and limited data analysis. Originally two measurements were proposed - total water and carbon dioxide - both to be made from the NASA WB-57F aircraft. Due to space limitations, the carbon dioxide instrument could not be accommodated on the WB-57F. Although attempts were made to find a home for this instrument on the CIRPAS Twin Otter, the requisite additional funding to achieve this move was not available. Thus, no further work was done with carbon dioxide measurements under this grant.

Personnel:

Funding from this grant supported the work of a graduate student, Gannet Hallar, for the two-year duration of the project. Ms. Hallar received her Ph.D. in December 2003 and is now employed as a NRC postdoctoral fellow with Anthony Strawa at NASA Ames Research Center. The salary of the principal investigator was paid during the field phases of CRYSTAL-FACE (May and June/July 2002) and partially during fall 2003 when she was on sabbatical. In addition, the services of a mechanical engineer (Steven Lane) and an electrical engineer (Roger Gunderson) were used during the premission preparations and integration and test flight series in Houston.

Instrumentation and Performance:

An existing closed-path tunable diode laser hygrometer (CLH) was employed for the measurements of total water made during CRYSTAL-FACE. This instrument had flown previously on the NASA DC-8 during the SAGE III Ozone Loss and Validation Experiment (SOLVE) and also on the NCAR C-130 during some local flights designed to test the extent of water vapor interference in carbon dioxide measurements. The instrument was largely unchanged from previous studies, but a new inlet appropriate to the WB-57F wingpod was constructed. In order to minimize the impact on the over-subscribed right wingpod and to achieve good thermal control of the inlet temperature, the CLH inlet was made of carbon-fiber/epoxy composite. Considerable effort was spent to design and build the lightest possible mounting hardware and design relatively low-power inlet heaters. As a result, the instrument and mounting hardware came in below the NASA/JSC-imposed weight cap of 35 lbs.

Data were obtained on all test flights during May 2002 and during all but one mission flight in July 2002 (the one lost flight was due to an unplugged instrument power cable). Instrument performance during the test flights was good, but the data are not science-quality, as a variety of tests were performed to optimize the inlet configuration and heating. Data on all mission flights is of high quality, despite some difficulties caused by flying through wet low-altitude air masses and dense anvils, which saturated the instrument response.

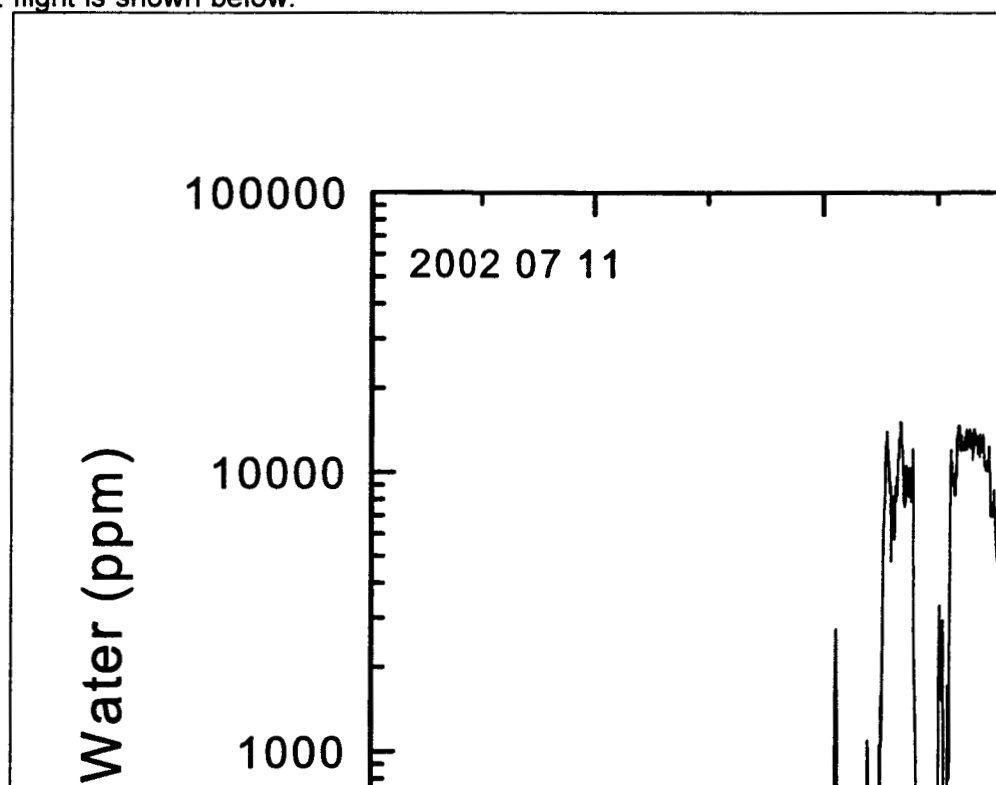
Data:

Measurements of "total water" (the sum of gas-phase and particulate water) were obtained every 1.5 seconds from takeoff to landing. By using a forward-facing, sub-isokinetic inlet, water contained in the particulate phase was inertially enhanced above its true ambient concentration by factors of 40 to 100, depending on aircraft speed and altitude. As a result, the instrument is sensitive to very rare clouds and becomes saturated in dense ones. Conversion of the "raw" data to a more useful form, such as

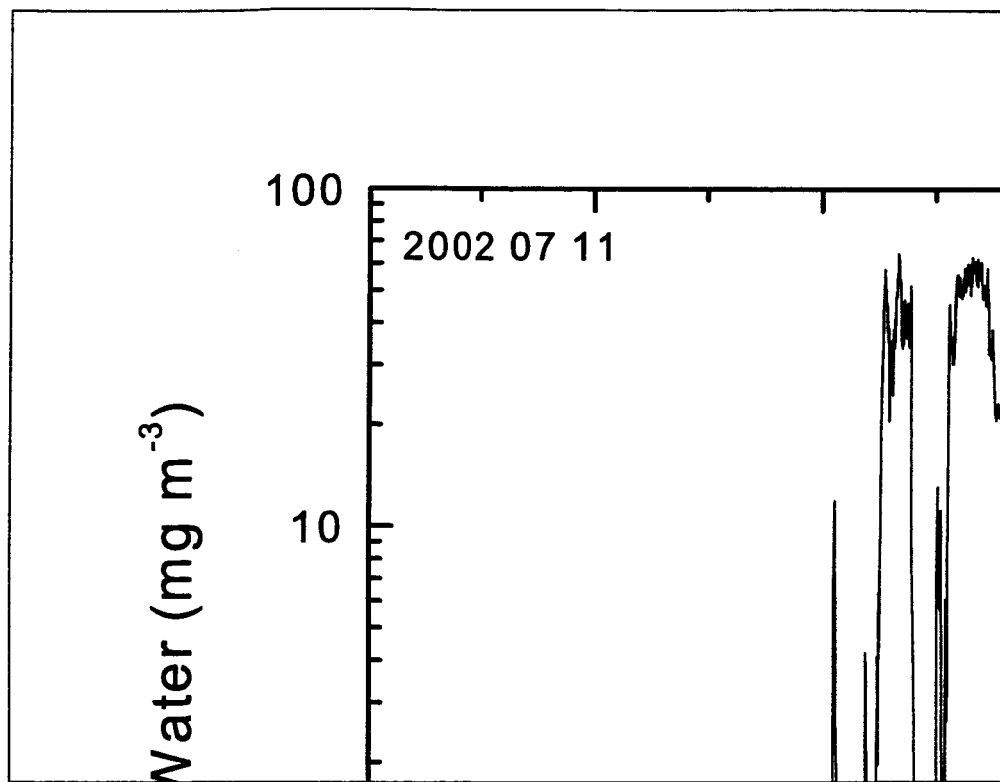
cloud ice water content (IWC), requires removal of signal due to gas-phase water (measured by another instrument such as the JPL Laser Hygrometer, JLH) and calculation of the inlet enhancement factor. Before post-mission calibrations were carried out, only the "raw" total water data were archived on the mission site. Following extensive calibrations (see below), an updated data product - IWC in both mixing ratio units (ppm) and in mass units (mg m^{-3}) - was archived on the mission site.

Key Results:

During CRYSTAL-FACE, observations of cloud ice water content were made under a variety of conditions, ranging from ultra-thin subvisual cirrus to dense anvils. Our assessment of instrumental uncertainties suggests that the CLH was able to measure cloud water contents from about 0.01 mg m^{-3} to about 1 g m^{-3} , a dynamic range of 10^5 , with an accuracy of better than $\pm 15\%$. An example of raw data and IWC for the 11 July 2002 flight is shown below.



Raw CLH data from a segment of the 11 July 2002 CRYSTAL flight.



Ice water content calculated from the CLH instrument observations on 11 July 2002.

In a number of cases, such dense clouds were sampled that the instrument response in the second-harmonic channel (which is more sensitive to small mixing ratios) was saturated. Direct absorption signals were also monitored, although less frequently. We originally expected to be able to produce 20-second data during periods of time when very wet clouds were sampled. However, extensive laboratory calibrations provided the information necessary to account for the instrument response in saturated regions; as a result, 1.5-second data are now available throughout every flight.

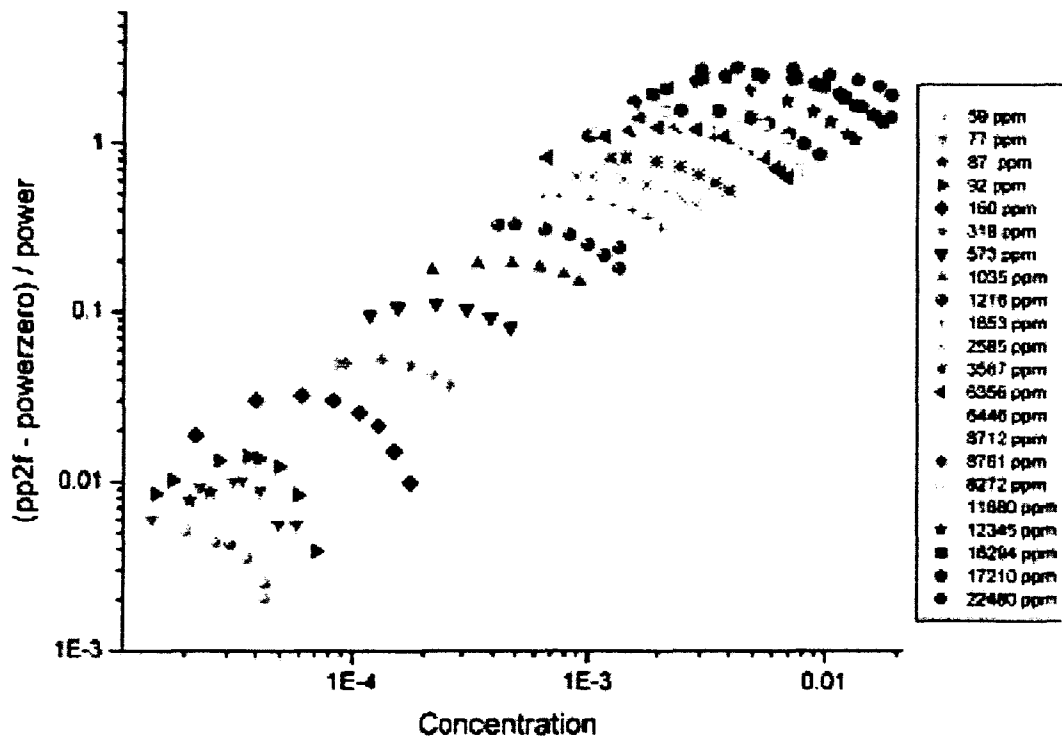
Calibrations:

Considerable effort was put into calibrations for the CLH data. Intercalibrations between the JPL and Colorado laser hygrometers (JLH and CLH) took place during the first week of November at JPL. This process improved the direct comparison of the gas-phase and total water measurements and resulted in a more accurate calculation of cloud ice water content, particularly in thin clouds.

As part of her doctoral thesis work, Dr. Hallar devised a calibration system that would enable testing of the CLH response over the wide range of pressures and water amounts sampled during CRYSTAL-FACE. Dr. Hallar worked in collaboration with Dr. Teresa Campos of NCAR's Research Aviation Facility to create this calibration system. Dr. Campos operates NCAR's tunable diode laser hygrometer, which is of similar design to the CLH, and was flown on the Twin Otter during CRYSTAL-FACE. Both hygrometers were calibrated with water vapor mixtures generated by a NIST-traceable LiCor 610 Dewpoint Generator and calibrated MKS 640 mass flow controllers. Special care was taken to hold the pressure of the dewpoint generator fixed with a pressure-control circuit to insure accurate water output. The internal pressures of the two hygrometers were also maintained with pressure-control circuitry and a vacuum pump.

A compilation of data from these calibrations is shown below. Water vapor mixing ratios ranged from 60 to 24,000 ppm for pressures between 100 and 1000 hPa; corresponding dewpoints range from -63 to +25 °C. The figure below shows laser signal (on the y-axis) as a function of absolute water amount (on the x-axis). Each curve represents a different water mixing ratio, and each point a different pressure at a fixed mixing ratio.

ALL Calibrations: March - July 2003 at NCAR RAF



Summary of CLH calibration data, showing laser signal as a function of water abundance (kg m^{-3}) for a range of mixing ratios. Each point along a mixing ratio curve represents a different pressure.

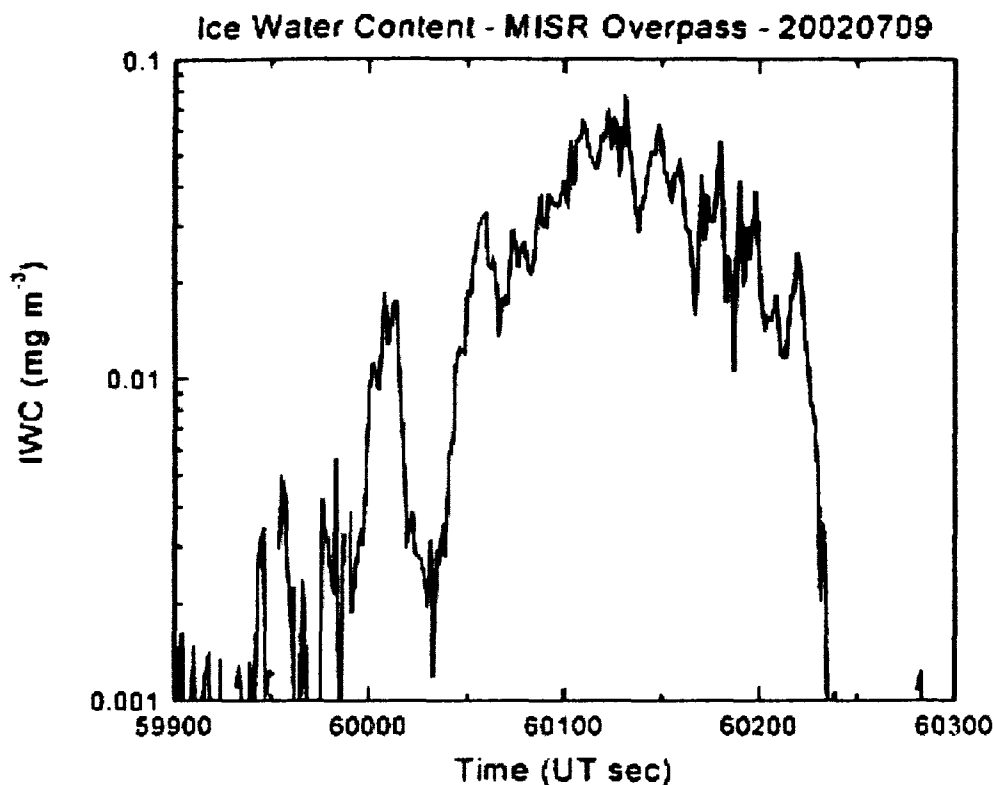
These curves were used to generate a complex function for calculating water vapor mixing ratio from observed laser signals, pressure, and temperature. This function was coded into a new data analysis algorithm that runs in IDL; subsequent improvements to that code enable it to process data from a six-hour flight in less than one minute.

As a result of Dr. Hallar's efforts, we have significantly improved our confidence in the CLH data. Error analysis shows that water vapor mixing ratios can be determined to better than $\pm 15\%$ (2σ) over the pressure range 100-1000 mb, and for water mixing ratios from 10 to 25,000 ppm. Results from this work, and from the calculations described below, are the subject of a manuscript in preparation for the *Journal of Atmospheric and Oceanic Technology*.

Enhancement Efficiency and Inlet Performance:

One of the key features of the CLH instrument is its sub-isokinetic inlet. The inertial enhancement of particles within this inlet substantially improves signal-to-noise ratios in

thin cirrus clouds, enabling measurement of IWC values as small as 0.01 mg m^{-3} . An example of this sensitivity is shown below, illustrating IWC in a very thin cirrus sampled during a MISR overpass.



Example of IWC measured by CLH during an encounter with an isolated very thin cirrus cloud at 18 km altitude, east of the Yucatan peninsula.

To report accurate IWC values, it is important that we understand well the performance of the instrument inlet. The two most critical factors are: to what extent are particles completely evaporated?, and how does the enhancement efficiency vary with particle size? The first of these questions was addressed with a heat-transfer model that Dr. Hallar adapted. Using the known temperature of the inlet system (which is maintained with resistive heaters and controlled to 40°C) and the mass flow-rate through the instrument, we have shown that spherical particles with diameters $\leq 100 \mu\text{m}$ are completely evaporated. Because of greater surface area-to-volume ratios, even larger columnar or dendritic particles are completely evaporated. This model is conservative, in that it assumed a straight path through the instrument. In reality, there are two 90° bends; it is likely that large particles impact the walls in these bends and shatter. The resulting smaller pieces are expected to evaporate much more quickly than the "parent" particle, so the evaporation efficiency is likely to be quite high for particles up to $300\text{--}400 \mu\text{m}$.

We carried out a preliminary assessment of the particle enhancement efficiency as a function of particle size using existing analytical frameworks, based on the classic studies of Belyaev and Levin (1972) and Vincent (1987). These give upper and lower bounds to the likely enhancement efficiency, and show that particles smaller than $10 \mu\text{m}$

diameter are not substantially enhanced relative to ambient conditions. A more detailed study of the inlet properties is currently being carried out with funding from the NASA Radiation Sciences Program.

Publications, Presentations, and Future Plans:

In addition to fluid dynamical calculations related to particle sampling by the CLH inlet, we are currently preparing for participation in the NASA-sponsored Midlatitude Cirrus Experiment (MidCiX). Among the goals of this experiment are intercomparisons of various instruments for measurements of IWC, particle-size distributions, and water vapor; comparison of ground-based remote sensors with in situ observations of cloud properties; and testing of retrieval algorithms for existing and new satellite sensors.

A new graduate student, Lars Kalnajs, is working with CRYSTAL-FACE data as part of a class project for a remote-sensing course. He is focussing on comparisons of in situ observations to remotely sensed data in thin cirrus, specifically the thin cirrus case shown above. We anticipate writing a paper for *Geophysical Research Letters* on the basis of Mr. Kalnajs' project.

A.G. Hallar, *Use of a Tunable Diode Laser Closed Path Hygrometer for the Measurement of Total Water in Tropopause Cirrus*, Ph. D. Thesis, University of Colorado, 2003.

A.G. Hallar, L.M. Avallone, R.L. Herman, and T. J. Garrett, *Contrast and comparisons of in situ measurements of IWC, extinction and size distributions during two cirrus cloud case studies (7/9/2002 and 7/11/2002)*, poster presented at the CRYSTAL-FACE Science Team Meeting, Salt Lake City, UT; February 2003.

L.M. Avallone, A.G. Hallar, R.L. Herman, and T. L. Thompson, *Measurements of ice water content in very thin cirrus*, talk presented at the CRYSTAL-FACE Science Team Meeting, Salt Lake City, UT; February 2003.

A.G. Hallar, L. M. Avallone, R. L. Herman and T. J. Garrett, *Measurements of ice water content and extinction, and calculated effective radius in tropical cirrus during CRYSTAL-FACE*, poster presented at the American Geophysical Union - European Geophysical Society Joint Meeting, Nice, France; April 2003.

L. M. Avallone and A. G. Hallar, *Measurements of ice water content in low-latitude cirrus clouds*, poster presented at the American Geophysical Union Meeting, San Francisco, December 2003. (copy included with hard-copy of this report)